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Williams AFB Site ST012 Technical Support
Review of Weekly Progress Report 18-May-15
Energy Balance for ST012 Soil Volumes through May 18, 2015

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A primary purpose for performing an energy balance during steam injection, and assessing the related hydraulic containment, is to determine the potential for NAPL to be transported away from the thermal treatment zone. Heated NAPL moving under pressures associated with steam injection will move with the steam and/or hot water. Hence, if water flow is outward, then NAPL flow is outward and this flow is enhanced if heated. The transport of energy outside the target treatment zones is an indicator of such NAPL migration. Adversely displaced NAPL increases the burden on later treatment by other means to meet the remedial action objectives.

The energy requirement for heating the soil at ST012 is presented in Table 5.5 of Appendix D in the SEE Work Plan. The energy value reported in Table 5.5 is 786,533,000 BTU/F based on a soil volume of 615,149 cubic yards (cy). This volume is the thermal treatment zone (TTZ) multiplied by a factor of 1.5 (referred to as the Heated Zone, HZ), i.e., the volume of the heated zone is 50% larger than the TTZ. The required energy for heating the HZ soil volume to a specified temperature above ambient is presumably calculated by multiplying the provided energy value by the change in soil temperature.

$$E_{soil} = (786{,}533{,}000\ BTU/F)(T - T_{amb})$$

The weekly progress report through May 18, 2015 presents in Figure 20 a net energy in the soils (energy injected – energy extracted) of around 32,000,000 kWh (~109,194 MBTU). The energy injected as steam is shown as about 43,000,000 kWh and the extracted energy totals about 11,000,000 kWh. Using this soil energy value and an ambient temperature of 82 F (28 C) as indicated by the subsurface temperature monitoring, we find after rearranging the expression above,

$$T = T_{amb} + \frac{E_{soil}}{786{,}533{,}000 \frac{BTU}{F}} = 82\ F + \frac{109{,}194{,}000{,}000\ BTU}{786{,}533{,}000 \frac{BTU}{F}}$$
$$T\ = 221\ F = 105\ C$$

Based on the provided data, the average soil temperature throughout the HZ of all layers is expected to be 221 F (105 C) on May 18. However, the average temperatures presented on May 18 in Figure 6 for all layers of the TTZ (smaller than the HZ) are approximately 192 F in the LSZ, 140 F in the UWBZ and 90 F in the CZ; all three averages are well below the predicted average of 221 F. This large discrepancy in temperatures indicates significant energy has been transported outside the HZ volume rather used to further heat the HZ soils.

For application to individual zones (i.e., CZ, UWBZ and LSZ), the total heating value of the soil provided in Appendix D can be converted to a more conventional soil heat capacity by dividing 786,533,000 BTU/F by the soil volume considered,

$$u_{soil} = \frac{786{,}533{,}000\ BTU/F}{615{,}149\ \text{cy}} \left(\frac{1\ cy}{27\ ft^3}\right) = 47.4\ \frac{BTU}{F\ ft^3}$$

With this unit soil heat capacity, the energy stored within each zone can be calculated from its soil volume and average temperature. For example, in the LSZ,

$$E_{soil,LSZ} = u_{soil} V_{LSZ}(T_{LSZ} - T_{amb}) = \left(47.4\ \frac{BTU}{F\ ft^3}\right)(385{,}469 \times 27\ \ ft^3)(192F - 82F)$$
$$= 54{,}208\ MBTU = 15{,}886{,}100\ kWh$$

The soil volume for the HZ (from Table 5.3 of Appendix D) and the calculated energy content for all three soil zones are provided in the table below.

Parameter	**LSZ**	**UWBZ**	**CZ**
Thermal Treatment Zone Soil Volume, cy	256,979	113,212	39,957
Heated Zone Soil Volume, cy	385,469	169,818	59,936
Average Temperature (18-May-15), F	192	140	90
Temperature Change from Ambient, F	110	58	8
Volumetric Heat Capacity (u_{soil}), BTU/F/ft^3	47.4	47.4	47.4
Soil Energy Content (E_{soil}), MBTU	54,208	12,592	613
Soil Energy Content (E_{soil}), kWh	15,886,100	3,690,200	179,600
Total Soil Energy Content (E_{soil}), MBTU	67,413		
Total Soil Energy Content (E_{soil}), kWh	19,755,900		

The weekly progress report through May 18, 2015 presents the net energy in the subsurface of around 32,000,000 kWh (~109,194 MBTU). This total energy exceeds the total soil energy content calculated above using average soil temperatures. Based on the reported net energy in the soil, the average zone temperatures, and assuming the larger volume of the HZ indicates that approximately 40% of the energy in the soil is located outside the hypothetical HZ. For the TTZ, the majority of the energy in the subsurface is outside the thermal treatment zone compared to inside; about 60% of the subsurface energy is beyond the TTZ boundaries. The transport of a large fraction of the energy away from the TTZ is inconsistent with the concept of hydraulic containment wherein water flow is toward the TTZ.

Additional Considerations for the Energy Balance and Hydraulic Containment

The soil thermal properties used to calculate this energy value of 786,533,000 BTU/F were not provided in Appendix D. However, the volumetric energy content of soil with water and steam vapor is a basic calculation provided by numerous references (e.g., Marx & Langenheim, 1959; Mandl & Volek, 1969; Menegus & Udell, 1985):

$$\begin{gathered} Soil\ Energy\ Content\ per\ Unit\ Volume\ (with\ steam\ vapor\ present) = \\ Energy\ in\ Solid\ Rock + Energy\ in\ Water\ + Energy\ in\ Steam\ Vapor = \\ e_{soil,steam} = \left[\rho_r c_{pr}(1-\varphi) + \rho_w c_{pw}\varphi S_s\right](T_s - T_{amb}) + \rho_v h_v \varphi (1 - S_s) \end{gathered}$$

In this expression, the parameter S_s represents the saturation of liquid water in the soil pore space, just as it does in the vadose zone. Pore space not occupied by liquid water is occupied by steam vapor. Notation and typical values for the other parameters in this expression are provided in the table below.

Parameter	**T_s** (266 °F)
Total Porosity (ϕ), nd	0.30
Solid/Rock Density (ρ_r), lb/ft^3	165.5
Solid/Rock Heat Capacity (c_{pr}), BTU/lb/°F	0.24
Water Density (ρ_w), lb/ft^3	58.34
Water Heat Capacity (c_{pw}), BTU/lb/°F	1.02
Steam Vapor Density (ρ_v), lb/ft^3	0.094
Steam Vapor Enthalpy (h_v), BTU/lb	1,170

Substituting these parameters into the steam zone energy expression above yields the energy content in the soil per unit volume as a function of the pore space occupied by liquid,

$$e_{soil,steam}(BTU/ft^3) = [27.8 + (18.3)S_s](266 - 82) + 33(1 - S_s)$$

Substituting a value of one for the water saturation (no steam vapor) and dividing by the temperature difference yields the soil heat capacity when saturated with liquid water,

$$u_{soil}\left(\frac{BTU}{F\ ft^3}\right) = 27.8 + 18.3 = 46.1\ \frac{BTU}{F\ ft^3}$$

This calculated heat capacity of 46.1 is close to the value of 47.4 determined from the energy parameter in Appendix D, Table 5.5. The small difference is likely the result of slightly different parameter values (i.e., water and solid densities and heat capacities, steam zone temperature). The two soil heat capacity values are effectively equal with a water saturation of one indicating the SEE modeling presented in Appendix D did not consider the formation of a steam bubble in the subsurface and brings into question the consideration of steam bubble formation on hydraulic containment.

The formation of a steam bubble, commonly referred to as a steam zone, requires the inclusion of steam vapor in the calculation of the soil energy content. This is demonstrated in the expression above when S is less than one. Therefore, if a steam zone exists and is growing, the energy balance should account for it. Differing liquid/vapor contents in the soil pore space were input to the simple expression above for the soil energy content to illustrate the variation in soil energy. The results are provided in the table below,

S_s Liquid Saturation	$1-S_s$ Steam Vapor Saturation	u_{soil} (BTU/F/ft^3)	$e_{soil,steam}$ (BTU/ft^3)
1.00	0.00	46.1	8,476
0.75	0.25	41.6	7,644
0.50	0.50	37.0	6,812
0.25	0.75	32.5	5,980

These calculations demonstrate that the energy content in soils containing a steam vapor are lower than the energy content in soil saturated with water at steam temperature. Therefore, where a steam bubble or steam zone is created, the energy required for heating is less than the energy predicted by the energy value provided in Appendix D. Assume for example that steam vapor occupies 50% of the pore space, the energy required to heat the soil volume is only 6,812 BTU/ft^3 or 20% less than water-saturated soil value of 8,476. If steam vapor occupies pore space in the TTZ, as intended during steam injection, an even larger fraction than 40% of energy in the soil has been transported beyond the boundaries of the hypothetical HZ and contradicts the concept of a net inward flow of water.

The energy balance is inter-related to mass and volume balances (e.g., the existence of steam vapor versus liquid water in soil pore spaces) and hydraulic containment. Consider the mass of water in a unit volume of soil at steam temperature but without steam vapor,

$$m_{water,saturated} = \rho_w \varphi = \left(58.3\ \frac{lb}{ft^3}\right)(0.30) = 17.5\ \frac{lb}{ft^3}$$

Consider next the mass of water in a unit volume of soil that has 50% of its pore space occupied by steam vapor,

$$
\begin{aligned}
m_{water,steam} &= \rho_w \varphi S_s + \rho_v \varphi (1 - S_s) \\
&= \left(58.3\ \frac{lb}{ft^3}\right)(0.30)(0.50) + \left(0.094\ \frac{lb}{ft^3}\right)(0.30)(0.50) \\
&= 8.8\ \frac{lb}{ft^3}
\end{aligned}
$$

This simple mass balance demonstrates that a 1:1 ratio of mass injected versus mass extracted is not valid for describing hydraulic containment when a steam bubble exists. A unit volume previously occupied by 17.5 pounds of water holds only 8.8 pounds of water if a modest steam bubble exists (S=0.5). The displaced 8.7 pounds of water must be accounted for in the extraction to maintain hydraulic control. This water displacement phenomenon is well described by EPA (Davis, 1998),

> *Initially, the steam that is injected will heat the well bore, and the formation around the injection zone of the well. The steam condenses as the latent heat of vaporization of water is transferred from the steam to the well bore and the porous media where it enters the formation. As more steam is injected, the hot water moves into the formation, pushing the water initially in the formation (which is at ambient temperature) further into the porous media. When the porous media at the point of steam injection has absorbed enough heat to reach the temperature of the injected steam, <u>steam itself actually enters the media, pushing the cold water and the bank of condensed steam (hot water) in front of it</u>.*

As implied in the EPA description and demonstrated by the simple water mass calculation, the ability to estimate the volume of the steam zone in the subsurface during steam injection is integral to the determination of hydraulic control. The volume of the steam zone is a major parameter in assessing an acceptable water mass balance. Put another way, one pound of uncondensed steam vapor displaces roughly 500 to 600 pounds of liquid water. Assessing hydraulic containment should include displacement of groundwater by steam vapor and ambient groundwater flow as well as condensed steam. Balances in the weekly progress reports consider only condensed steam and are inadequate for assessing hydraulic containment.

References

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